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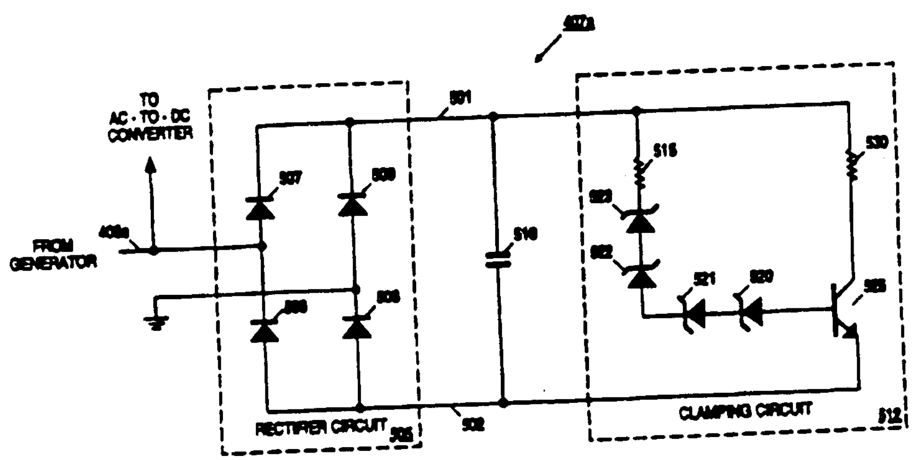

(57) Abstract

A circuit for suppressing transient voltages in an electrical signal transmitted by a first transmission line. The circuit comprises a rectifier circuit (505) having a first input, a second input, a first output, and a second output, wherein the first input is coupled to the first transmission line (406a) and the second input is coupled to a second transmission line. A positive rail (501) is coupled to the first output of the full-wave rectifier circuit, and a negative rail (502) is coupled to the second output of the full-wave rectifier circuit. A capacitor (510) is coupled between the positive and negative rails. The capacitor stores the energy of a transient so that the energy of the transient may be dissipated over time. A clamping circuit (512) is coupled across the capacitor. The clamping circuit defines a clamping voltage for the capacitor and dissipates charge stored in the capacitor when the capacitor is charged to a voltage exceeding a clamping voltage such that the voltage of the capacitor is reduced to the clamping voltage.

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TRANSIENT SUPPRESSOR FOR ELECTRONICS SYSTEMS

FIELD OF THE INVENTION

This invention relates generally to the suppression of transient voltages in electrical systems. Specifically, this invention relates to suppressing repeatable transient voltages in power electronics applications.

ART BACKGROUND

Transient voltages or "surges" occur in all electrical and electronic systems. Some transient voltages are the result of a sudden release of energy that has been previously stored by stray parasitic capacitances and inductances of the electrical system. Other transient voltages are the result of a sudden injection of energy into the electrical system by a source external to the electrical system.

Transient voltages may occur on a random basis or on a repeatable basis. Random transient voltages are typically generated by sources external to the electrical system. For example, lightning is a source of random transient voltages. Another example is switching the equipment "on and off."

Repeatable transient voltages may occur at a fixed or variable frequency and are typically generated internally by an electrical system. For power electronics systems, repeatable transients may be the result of the rapid switching of current by power electronics converters in the system. Such switching is often undertaken to convert the frequency, voltage, or current of an electrical signal.

Regardless of the source and frequency of their occurrence, transient voltages can damage electrical and electronic equipment. For electrical machines such as motors and generators, transient voltages can destroy the insulation of the wiring, resulting in premature equipment breakdown and failure. Therefore, transient voltage suppressors are important devices to better ensure continued operation of such equipment.

Repeatable transient voltages are of increasing concern in the area of power electronics converter-fed variable speed drive systems, one example of which may be found in windpower electronics

systems, which use wind turbines for supplying electrical energy to an AC electric power grid. If the electrical power generated by a wind turbine is to be supplied to an AC electric power grid, the electrical signal must have a constant frequency that is synchronized to the frequency of the AC electric power grid. Synchronizing the frequency of the electrical signal output by the generator of the wind turbine to the frequency required by the AC electric power grid may require the use of power electronics converters which can be a source of repeatable transients. Further, the nominal voltage of the electrical signal supplied by the wind turbine must be the nominal voltage of the AC electric power grid. AC electric power grids typically require a 480 volt signal at 60 Hz.

Variable speed wind turbines such as the one described in U.S. Patent No. 5,083,039, issued to Richardson et al. on December 15, 1992, and commonly assigned to U.S. Windpower Inc. of Livermore, California, are currently used to supply electricity to AC electric power grids. By varying the rotor speed of the wind turbine in varying wind conditions, improved energy conversion can be achieved over a range of wind speeds. The electrical signal directly generated by the generator of a variable speed wind turbine has a frequency that varies with the speed of the wind that drives the wind turbine. Therefore, the frequency of the electrical signal at the outputs of the generator of a variable speed wind turbine is not necessarily synchronized to the frequency of the utility line. Therefore, the electrical signal output by the generator of a variable speed wind turbine must be converted to have the appropriate voltage and frequency characteristics.

Power electronics converter circuits rapidly switch the AC signal output by the generator of the wind turbine to convert the AC voltage to a DC voltage. This rapid switching results in repeatable transient voltages that often exceed the voltage rating of the insulation of the electrical machine. These repeatable transient voltages should be suppressed to better ensure continued operation of the wind turbine.

Figures 1-3 show different prior art circuits and devices for suppressing transient voltages. As shown in each of the Figures 1-3, a load 102 is coupled between a line 101 and ground for receiving an electrical signal from the line 101. Each of the suppressor circuits or devices is coupled across the load 102 to provide an alternative conduction path for transient voltages when transient voltages occur.

Figure 1 shows an RC snubber circuit 103 coupled across the load 102. The RC snubber circuit 103 includes a dissipating resistor 105 coupled in series with a capacitor 110. The RC snubber 103 attenuates transient voltages. Even when transient voltages do not appear at the line 101, some current flows through the dissipating resistor 105, which over time results in a large amount of power dissipation in the dissipating resistor 105. To adequately suppress repeatable transient voltages, the level of attenuation of the RC snubber typically must be increased, which results in a corresponding increase in the amount of power dissipated in the dissipating resistor 105.

Figure 2 shows a metal oxide varistor (MOV) 205 coupled across the load 102. The MOV 205 is a non-linear device having a resistance that varies with the voltage applied to the MOV 205. For normal operation, the MOV 205 acts as a near open circuit. When a transient voltage having a magnitude beyond a breakdown voltage for the MOV 205 is present on the line 101, the MOV 205 becomes highly conductive, and the energy of the transient voltage is diverted away from the load 102. The MOV 205 thus clamps the voltage of the line to a safe operating voltage. Unfortunately, the relatively small amount of average power that can be dissipated by an MOV 205 typically makes the MOV 205 unsuitable for suppressing repeatable high energy transient voltages.

The average power dissipation required of an MOV to suppress a repeatable transient voltage is expressed in terms of the amount of energy (watt-seconds) per pulse multiplied by the number of pulses per second. Repeatable transient signals typically observed for a variable speed wind turbine typically require an average power dissipation of approximately 400 watts. Although MOVs can dissipate

high energy transients, a typical MOV can only provide approximately two watts of average power dissipation.

Furthermore, the clamping voltage of the MOV 205 depends on the amount of energy in the transient such that a higher energy transient voltage typically results in a higher clamping voltage. Uncertainty about the energy contained in each transient makes it is difficult to predict whether the MOV 205 can successfully suppress all high energy transients.

Figure 3 shows a prior art transient suppressor circuit 300 according to U.S. Patent No. 4, 849, 845, issued of Dwight Schmitt, and assigned to Sundstrand Corporation. The transient suppressor 300 includes two sense and control circuits 301a and 301b coupled across the load 102, wherein each of the sense and control circuits 301a and 301b detects transient voltages for a half-wave of the AC electrical signal provided by the line 101. For example, sense and control circuit 301a is responsible for controlling the suppression of positive transient voltages, and sense and control circuit 301b is responsible for controlling the suppression of negative transient voltages. Each control circuit 301a and 301b causes a corresponding transistor 302a or 302b to switch on when a transient voltage is detected. When a transistor 302a or 302b is switched on, a conductive path is created between the line 101 and ground. Each conductive path includes a dissipating resistor 303a or 303b for dissipating power and a diode 304a or 304b to better ensure that current flows in only one direction for each conduction path. Each of the control circuits 301a and 301b includes circuitry for actively monitoring the voltage of the line 101 and requires a separate power supply to operate. This typically makes the cost of the transient suppressor circuit 300 greater than that of other prior art transient suppressor circuits and devices.

Each of the suppressor circuits, including the RC snubber 103, the MOV 205, and the transient suppressor circuit 300 immediately dissipate the energy of the transient voltage in the dissipating resistor or MOV when a transient voltage appears across the load 102. This

results in high clamping voltage amplitude and requires a device capable of dissipating large amounts of power.

SUMMARY OF THE INVENTION

A circuit for suppressing transient voltages in an electrical signal transmitted by a first transmission line is disclosed. The circuit comprises a rectifier circuit having a first input, a second input, a first output, and a second output, wherein the first input is coupled to the first transmission line and the second input is coupled to a second transmission line. A positive rail is coupled to the first output of the rectifier circuit, and a negative rail is coupled to the second output of the rectifier circuit.

A capacitor is coupled between the positive and negative rails. The capacitor stores the energy of a transient so that the energy of the transient may be dissipated over time. A clamping circuit is coupled across the capacitor. The clamping circuit defines a clamping voltage for the capacitor and dissipates charge stored in the capacitor when the capacitor is charged to a voltage exceeding a clamping voltage such that the voltage of the capacitor is reduced to the clamping voltage. In the absence of transient voltages that exceed the clamping voltage, the capacitor is charged to the clamping voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects, features, and advantages of the method and apparatus of the present invention will be apparent from the following detailed description of the invention in which:

FIGURE 1 shows an RC snubber circuit of the prior art.

FIGURE 2 shows a metal oxide varistor (MOV) of the prior art.

FIGURE 3 shows a transient voltage suppressor circuit of the prior art.

FIGURE 4a shows a power electronics system including improved transient voltage suppressor circuits.

FIGURE 4b shows a power electronics system including an improved transient voltage suppressor circuit.

FIGURE 5 shows a single-phase transient voltage suppressor circuit according to a first embodiment.

FIGURE 6A shows waveforms for a transient voltage suppressor circuit of the first embodiment.

FIGURE 6B shows an output waveform for the transient voltage suppressor circuit of the first embodiment.

FIGURE 7 shows a three-phase transient voltage suppressor circuit of a second embodiment.

FIGURE 8 shows a three-phase/line-to-ground transient voltage suppressor circuit.

DETAILED DESCRIPTION

Figure 4a shows a power electronics system 400 that includes an electrical machine 405, an AC-to-DC converter 410, DC voltage link 415, and a DC-to-AC inverter 420 having outputs coupled to an AC electrical power grid 425. The power electronics system 400 may be part of a variable speed drive system such as a wind turbine, wherein the electrical machine 405 may be a generator driven by a turbine rotor (not shown), the rotational speed of which is determined by the force of a driving wind. The arrows of Figure 4a show current flow for the case wherein the electrical machine 405 is a generator. Alternatively, the electrical machine 405 may be an electrical load such as a motor. For such a case, the direction of the arrows indicating energy flow is reversed, the AC-to-DC converter 410 acts as a DC-to-AC inverter, and the DC-to-AC inverter 420 acts as an AC-to-DC converter. The electrical machine 405 may have a fixed or variable speed.

Assuming that the electrical machine 405 is a generator, the electrical machine 405 outputs three phases of a single AC electrical signal. According to one embodiment, the frequency of the AC electrical signal varies from 10 Hz to 80 Hz, depending on the speed of rotation for the electrical machine 405. AC electric power grid 425 requires a 60 Hz electrical signal having a nominal voltage of 480 volts. The AC electrical signal output by the electrical machine 405 must therefore be regulated and synchronized to the requirements of the AC electric power grid 425. If the electrical machine 405 is a motor, the AC electrical signal supplied by the AC electric power grid 425 must be regulated to the requirements of the motor 405.

To synchronize the AC electrical signal output by the variable speed electrical machine 405 to the requirements of the AC electrical power grid 425, the AC-to-DC converter 410 receives the three phases of the AC electrical signal via transmission lines 406a, 406b, and 406c. The AC-to-DC converter 410 converts the AC electrical signal to a DC signal. The DC voltage link 415, which includes a capacitor 418 coupled to a +DC rail 416 and a -DC rail 417, is charged to a DC voltage in response to the AC-to-DC converter 410. For the present

embodiment, the DC voltage of the DC voltage link 415 is equal to 750 volts. The DC-to-AC inverter 420 converts the DC voltage of the DC voltage link 415 to an AC electrical signal having the desired frequency and voltage characteristics for output to the AC electric power grid 425.

Both the AC-to-DC converter 410 and the DC-to-AC inverter 420 utilize switching to convert their respective input signals to the desired output signal. The switching frequency of the AC-to-DC converter 410 in one embodiment is 6 kHz, which results in a repeatable transient voltage signal having a frequency of 6 kHz on each of the transmission lines 406a, 406b, and 406c. The transient voltage signal is attributable to the parasitic inductances of the transmission lines 406a, 406b, and 406c, and to the parasitic capacitance of the variable speed electrical machine 405. Furthermore, each of the transmission lines mutually induces a repeatable transient voltage signal in the other transmission lines.

The repeatable transient voltage signal can be significant. For example, wherein the nominal maximum voltage of the AC electrical signal output by the electrical machine 405 is equal to 680 volts, it is not uncommon to have transient voltages equal to 1700 volts. For the present embodiment, the insulation of the electrical machine 405 is rated to withstand 900 volts continuously. It is therefore necessary to suppress the repeatable transient voltage signal to better ensure continued operation of the electrical machine 405. Of course, not all of the transient voltage pulses exceed the rating of the insulation. The largest transient voltage pulses typically have a duration of approximately 1-2 μS and occur once every 166 μS.

To suppress the transient voltages resulting from the inductance of a three phase transmission line, each phase may be provided with a single-phase transient suppressor circuit. Particularly, the transmission lines 406a, 406b, and 406c are provided with single-phase transient voltage suppressor circuits 407a, 407b, and 407c, respectively. To suppress the mutually induced transient voltages,

each of the transmission lines 406a, 406b, and 406c are coupled to a three-phase transient suppressor circuit 408.

Figure 4b shows the power electronics system 400 wherein a single three-phase/line-to-ground transient voltage suppressor circuit 409 is used. Each of the transient voltage suppressor circuits 407a-407c, 408, and 409 operate similarly. Unlike typical prior art transient voltage suppressor circuits and devices, the transient voltage suppressor circuits 407a-407c, 408, and 409 do not require the instantaneous dissipation of the energy of the transient. Instead, the energy of a transient may be stored and dissipated over time. Additionally, the present transient voltage suppressor circuits utilize clamping voltages such that the transient voltage suppressor circuits dissipate power only in the presence of a transient voltage beyond the clamping voltage. This reduces the power dissipation of the present transient voltage suppressor circuits when compared to prior art circuits such as the RC snubber. As will be described, the clamping voltage of the present transient voltage suppressor circuits is independent of the energy of the transient. The clamping voltage of typical MOVs is dependent on the energy of the transient.

The operation of a single-phase suppressor circuit is now described. As shown in Figure 5, the transient voltage suppressor circuit 407a includes a rectifier circuit 505, a capacitor 510, and a clamping circuit 512 for clamping the voltage of the capacitor. For one embodiment, the clamping circuit 512 includes a current limiting resistor 515, zener diodes 520-523, semiconductor switch 525, and dissipating resistor 530. The rectifier circuit 505 is a full-wave rectifier comprising a single-phase diode bridge circuit that includes diodes 506, 507, 508, and 509, wherein the transmission line 406a is coupled between the cathode of diode 506 and the anode of diode 507, and the conductor between the cathode of diode 508 and the anode of diode 509 is grounded. The positive rail 501 is coupled to the cathodes of diodes 507 and 509, and the negative rail 502 is coupled to the anodes of diodes 506 and 508.

One aspect of the transient voltage suppressor circuit 407a is the use of the capacitor 510 to store the energy of transient voltages. Because the capacitor 510 stores the energy of voltage transients, the energy of the transient voltages does not have to be dissipated instantaneously. This reduces the peak power dissipation requirement over typical prior art transient suppressor circuits and devices while simultaneously allowing dissipation of a higher average power. The use of the capacitor 510 as an energy storage device is discussed in more detail below.

Another aspect of the transient voltage suppressor circuit 407a is the use of zener diodes 520-523 to define a clamping voltage for the transient voltage suppressor circuit 407a. This clamping voltage is independent of the amount of energy in the transient, unlike the clamping voltages of prior art MOVs. The use of the zener diodes 520-523 to provide a clamping voltage is discussed in more detail below.

Returning to Figure 5, the rectifier circuit 505 has a first input coupled to the transmission line 406a and a second input coupled to ground, which may be the body of the electrical machine. The first and second outputs of the full-wave rectifier circuit 505 are coupled to a positive rail 501 and a negative rail 502, respectively. The capacitor 510 is coupled across the outputs of the rectifier circuit 505 to the positive and negative rails 501 and 502. The capacitor 510 smoothes the ripple voltage output by the rectifier circuit 505 to a DC voltage by acting as an energy storage device. When a transient voltage charges the capacitor 510 to a voltage exceeding the clamping voltage of the positive rail 501, the positive and negative rails 501 and 502 are coupled to one another via the semiconductor switch 525, which is shown as a bipolar junction transistor, such that the capacitor 510 discharges via the dissipating resistor 530 when the semiconductor switch 525 is "on."

Generally speaking, the semiconductor switch 525 may be considered to be a single pole single throw switch having a first pole coupled to the dissipating resistor 530, a second pole coupled to the negative rail 502, and a control terminal. The semiconductor switch

525 may be any suitable device including a bipolar junction transistors (BJT), a metal-oxide semiconductor field effect transistor (MOSFET), an insulated gate bipolar transistor (IGBT), or a junction field effect transistor (JFET). When the semiconductor switch 525 is a BJT, as shown, the first pole is the collector of the BJT, the second pole is the emitter of the BJT, and the control terminal is the base of the BJT. If the semiconductor switch 525 is a field effect transistor (FET), the first pole is the drain of the FET, the second pole is the source of the FET, and the control terminal is the gate of the FET.

To control the semiconductor switch 525, four zener diodes 520, 521, 522, and 523 are coupled in series between a current limiting resistor 515 and the base of the semiconductor switch 525. Any number of zener diodes can be used to provide the desired clamping voltage. The current limiting resistor 515 is coupled between the zener diode 523 and the positive rail 501 to limit and define the base current presented to the semiconductor switch 525 when the zener diodes 520-523 are conducting.

The zener diodes 520-523 clamp the DC voltage at the positive rail 501 to a value equal to the sum of the zener voltages for each zener diode. During normal operation, the positive and negative rails 501 and 502 are decoupled from one another such that the capacitor 510 does not discharge, and the capacitor 510 is charged to the clamping voltage. When the voltage of the positive rail 501 exceeds the sum of the zener voltages for the zener diodes 520-523, the zener diodes 520-523 become conducting, delivering a current to the base of the semiconductor switch 525.

The semiconductor switch 525 is switched on in response to the base current, and the capacitor 510 discharges through the dissipating resistor 530 and the semiconductor switch until the voltage at the positive rail 501 is the less than the sum of the breakdown voltages for the zener diodes 520-523. The zener diodes 520-523 then act as open circuits, and the base current is removed from the semiconductor switch 525 such that the semiconductor switch 525 is switched off, decoupling the positive rail 501 from the negative rail 502. The

dissipating resistor 530 is coupled between the positive rail 501 and the collector of the semiconductor switch 525, and the emitter of the semiconductor switch 525 is coupled to the negative rail 502. If the semiconductor switch 525 is a field effect transistor (FET), the positive rail 501 is coupled to the drain of the semiconductor switch 525, and the negative rail 502 is coupled to the source of the semiconductor switch 525.

The zener diodes 520-523 are chosen such that the DC voltage of the positive rail 501 is clamped to a value that is less than the breakdown voltage of the electrical machine insulation. For the present embodiment wherein the insulation breakdown voltage is equal to 900 volts, each zener diode has a zener voltage of 200 volts such that the DC voltage of the positive rail 501 is clamped at 800 volts. Although a single zener diode may be sufficient for certain uses of the transient suppressor circuit 407a, coupling several zener diodes in series is advantageous because zener diodes having a zener voltage equal to the desired clamping voltage may be cost-prohibitive or otherwise unavailable. Further, a zener diode typically has a power rating that limits the amount of current the zener diode can conduct for a given voltage. For example, the power rating for a single zener diode having an 800 volt breakdown voltage may be such that zener diode cannot conduct a base current sufficient to switch the semiconductor switch 525 on. By coupling several zener diodes in series, the voltage drop across each zener diode is reduced such that a greater amount of current may be conducted by each zener diode.

Because of the operating characteristics of the capacitor 510, a large transient voltage that exceeds the clamping voltage of the voltage transient suppressor circuit 407a results in only a relatively small increase in the voltage of the capacitor 510. The energy stored by a capacitor is given by the following, well known equation:

$$Energy = \frac{CV_C^2}{2}, \qquad (1)$$

wherein C is the capacitance of the capacitor 510, and V_C is the clamping voltage of the voltage suppressor circuit 407a. The

capacitance C and the clamping voltage V_C determine the energy stored in the capacitor 510 prior to the receipt of a transient voltage that exceeds the clamping voltage. For the present embodiment, the capacitance C is microfarad and the clamping voltage V_C is equal to 800 volts such that the amount of energy stored in the capacitor 510 is much greater than the energy of a single transient voltage pulse. When the capacitor 510 stores the energy of the transient voltage, the voltage of the capacitor increases proportionally to the square-root of the added energy. Typically the energy already stored in the capacitor is very much larger than the energy of a 1-2μS transient voltage, and the voltage of the positive rail 501 increases only slightly in response to such a transient. For example, 1700 volt transient may result in the positive rail 501 being charged to between 805 and 810 volts.

The capacitor 510 discharges at a rate given by the RC time constant of the transient voltage suppressor circuit 407a, wherein C is the capacitance of the capacitor 510, and R is the resistance value of the dissipating resistor. The values of R and C may be selected such that the capacitor 510 decays to the clamping voltage of the positive rail 501 before the next repeatable transient voltage pulse is received. For example, if the frequency of the repeatable transient voltage signal is 6 kHz, the RC time constant of the transient voltage suppressor circuit 407a is less than 166 μS.

Figure 6a shows plots of an input AC signal V_{in}, the voltage V_{CAP} across the capacitor 510, and the voltage V_R across the dissipating resistor 530. Curve 610 is the input AC signal. Curve 620 is the voltage across the capacitor 510, and curve 630 is voltage across the dissipating resistor 530. As shown, the capacitor 510 is charged between the clamping voltage V_C and the voltage defined by the added energy of a transient voltage exceeding the clamping voltage. The voltage across the dissipating resistor 530 can vary from between zero volts to the highest voltage to which the capacitor 510 is charged. The voltage across the dissipating resistor 530 may not go to zero, depending on the energy of a particular transient.

Figure 6b shows a plot of the input AC signal at the output electrical machine 405 due to the single-phase suppressor circuit 407a. As shown, the transients of the input AC signal that exceeded the clamping voltage V_C have been truncated to the clamping voltage V_C. The other transient voltages have not been affected. Note that the drawings of Figures 6a and 6b are not to scale. Wherein a typical transient lasts for approximately 1-2 µS, the time from transient to transient is 166 µS. Thus, for the present embodiment, the capacitor 510 is charged for 1-2 µS and may discharge for as long as 165-165 µS.

Figure 7 shows the three-phase transient voltage suppressor circuit 408 in more detail. The primary difference between the single-phase voltage suppressor circuits 407a-c and the three-phase voltage suppressor circuit 408 is the configuration of the rectifier circuit 505. For the three-phase voltage suppressor circuit 408, the rectifier circuit 505 is a three-phase full-wave diode bridge circuit including diodes 701, 702, 703, 704, 705, and 706. The three-phase rectifier circuit 505 includes three inputs, one each between the anode and cathode of each diode pair. For example, transmission line 406a is coupled between the cathode of diode 701 and the anode of diode 702; transmission line 406b is coupled between the cathode of diode 703 and the anode of diode 704; and transmission lined 406c is coupled between the cathode of diode 705 and the anode of diode 706. The cathodes of diodes 702, 704, and 706 are each coupled to positive rail 501. The anodes of diodes 701, 703, and 705 are each coupled to the negative rail 502.

Figure 8 shows the three-phase/line-to ground voltage transient suppressor circuit in more detail. The configuration of the rectifier circuit 505 for the three-phase/line-to-ground voltage transient voltage suppressor circuit 409 is different from the rectifier circuits for the single-phase and three-phase transient voltage suppressor circuits. For the three-phase/line-to-ground voltage suppressor circuit 409, the rectifier circuit 505 includes diodes 801, 802, 803, 804, 805, 806, 807 and 808. The three-phase/line-to-ground rectifier circuit 505 includes four inputs, one each between the anode

and cathode of each diode pair. For example, transmission line 406a is coupled between the cathode of diode 801 and the anode of diode 802; transmission line 406b is coupled between the cathode of diode 803 and the anode of diode 804; and transmission lined 406c is coupled between the cathode of diode 805 and the anode of diode 806; and ground it coupled between the cathode of diode 807 and the anode of diode 808. The cathodes of diodes 802, 804, 806, and 808 are each coupled to positive rail 501. The anodes of diodes 801, 803, 805, and 807 are each coupled to the negative rail 502. This configuration of the rectifier circuit 505 allows for a single transient voltage suppressor circuit to be used to suppress all voltage transients.

The clamping circuit 512 of the three-phase/line-to-ground voltage transient suppressor circuit 409 may be that as shown in Figures 5 and 7, but Figure 8 shows an alternative clamping circuit 512 that includes a resistor 820. The resistor 820 may be used as the clamping circuit 505 when the power of the repeatable transient is known. Wherein the clamping circuit 512 comprises a resistor 820, some current is typically flowing through the resistor 820 at all times. However, the size and complexity of the clamping circuit 512 is much reduced. Further, the operation of a resistor is less temperature dependent than the operation of the zener diodes and a switching transistor. If the desired clamping voltage V_C and the power P of the repeatable transient is known, the resistance value R of the resistor 820 may be discovered by using the following equation:

$$R = \frac{V_C{}^2}{P}.$$

If the power of the repeatable transient is not known, the resistance value R of the resistor 820 may be obtained experimentally by selecting a resistance value R and observing the value of the clamping voltage. The value of the clamping voltage is related to the resistance value R of the resistor 820 by the following equation:

$$V_C = \sqrt{PR}.$$

Thus, if the clamping voltage is greater than the desired value, the resistance value of the resistor 820 should be reduced. Conversely, if

the clamping voltage is less than the desired value, the resistance value of the resistor 820 should be increased.

The illustrative embodiments of the transient voltage suppressor circuit have been described in conjunction with a power electronics system. More specifically, the embodiments have been described with respect to a wind turbine; however, the transient voltage suppressor circuit may be advantageously used in any electrical or electronics system, whether coupled to a generator or an electrical load. Further, wherein the transient voltage suppressor circuit is especially useful for suppressing repeatable transient voltages, the transient voltage suppressor circuit suppresses random transient voltages in precisely the same manner.

In the foregoing specification the invention has been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the invention as set forth in the appended claims. The specification and drawings are, accordingly, to be regarded in an illustrative rather than restrictive sense.

CLAIMS

What is claimed is:

1. A circuit for suppressing transient voltages in an electrical signal transmitted by a first transmission line, the circuit comprising:
   a rectifier circuit having a first input, a second input, a first output, and a second output, wherein the first input is coupled to the first transmission line and the second input is coupled to a second transmission line;
   a positive rail coupled to the first output of the rectifier circuit;
   a negative rail coupled to the second output of the rectifier circuit;
   a capacitor coupled between the positive and negative rails; and
   a clamping circuit coupled between the positive and negative rails, the clamping circuit being operative to set a clamping voltage and to dissipate charge stored in the capacitor when the capacitor is charged to a voltage exceeding the clamping voltage such that the voltage of the capacitor is reduced to the clamping voltage.

2. The circuit of claim 1, wherein the rectifier circuit is a diode bridge circuit.

3. The circuit of claim 2, wherein the second transmission line is coupled to ground.

4. The circuit of claim 1, wherein the rectifier circuit includes a third input coupled to a third transmission line, each of the first, second, and third transmission lines for transmitting one phase of the electrical signal.

5. The circuit of claim 1, wherein the rectifier circuit includes a third input coupled to a third transmission line and fourth input coupled to ground, each of the first, second, and third transmission lines for transmitting one phase of the electrical signal.

6. The circuit of claim 1, wherein the clamping circuit comprises a resistor having a first terminal coupled to the positive rail and a second terminal coupled to the negative rail.

7. The circuit of claim 1, wherein the clamping circuit comprises:
   a zener diode having a cathode and an anode, the cathode being coupled to the positive rail, wherein a zener voltage of the zener diode sets a clamping voltage of the positive rail;
   a dissipating resistor having a first terminal and a second terminal, the first terminal being coupled to the positive rail; and
   a semiconductor switch having a first pole coupled to the second terminal of the dissipating resistor, a second pole coupled to the negative rail, and a control terminal coupled to the anode of the zener diode, the semiconductor switch for coupling the positive rail to the negative rail when a voltage of the positive rail exceeds the clamping voltage.

8. The circuit of claim 7, wherein the circuit further includes at least one additional zener diode coupled between the zener diode and the control terminal of the semiconductor switch such that a sum of the zener voltage of the zener diode and zener voltages for each of the additional zener diodes sets the clamping voltage of the positive rail.

9. The circuit of claim 8, wherein a current limiting resistor is coupled between the positive rail and the cathode of the zener diode.

10. The circuit of claim 7, wherein the semiconductor switch is a transistor having a base, an emitter, and a collector, the base being coupled as the control terminal, the collector being coupled as the first pole, and the emitter being coupled as the second pole.

11. The circuit of claim 7, wherein the semiconductor switch is a transistor having a gate, a drain, and a source, the gate being coupled

as the control terminal, the drain being coupled as the first pole, and the source being coupled as the second pole.

12. An electronics system, comprising:
a electrical machine;
a first transmission line coupled to the electrical machine for transmitting a first phase of an alternating current (AC) electrical signal;
a second transmission line coupled to the electrical machine for transmitting a second phase of the AC electrical signal;
a third transmission line coupled to the electrical machine for transmitting a third phase of the AC electrical signal; and
a first single-phase transient voltage suppressor circuit coupled between the first transmission line and ground, the single-phase transient voltage suppressor circuit including:
a rectifier circuit having a first input, a second input, a first output, and a second output, wherein the first input is coupled to the first transmission line and the second input is coupled to ground;
a positive rail coupled to the first output of the rectifier circuit;
a negative rail coupled to the second output of the rectifier circuit;
a capacitor coupled between the positive and negative rails; and
a clamping circuit coupled between the positive and negative rails, the clamping circuit being operative to set a clamping voltage and to dissipate charge stored in the capacitor when the capacitor is charged to a voltage exceeding the clamping voltage such that the voltage of the capacitor is reduced to the clamping voltage.

13. The electronics system of claim 12, wherein the clamping circuit comprises a resistor having a first terminal coupled to the positive rail and a second terminal coupled to the negative rail.

14. The electronics system of claim 12, wherein the clamping circuit comprises:

a zener diode having a cathode and an anode, the cathode being coupled to the positive rail, wherein a zener voltage of the zener diode sets a clamping voltage of the positive rail;

a dissipating resistor having a first terminal and a second terminal, the first terminal being coupled to the positive rail; and

a semiconductor switch having a first pole coupled to the second terminal of the dissipating resistor, a second pole coupled to the negative rail, and a control terminal coupled to the anode of the zener diode, the semiconductor switch for coupling the positive rail to the negative rail when a voltage of the positive rail exceeds the clamping voltage.

15. The electronics system of claim 14, wherein the first single-phase transient voltage suppressor circuit further includes at least one additional zener diode coupled between the zener diode and the control terminal of the semiconductor switch such that a sum of the zener voltage of the zener diode and zener voltages for each of the additional zener diodes sets the clamping voltage of the positive rail.

16. The electronics system of claim 15, wherein a current limiting resistor is coupled between the positive rail and the cathode of the zener diode.

17. The electronics system of claim 14, wherein the semiconductor switch is a transistor having a base, an emitter, and a collector, the base being coupled as the control terminal, the collector being coupled as the first pole, and the emitter being coupled as the second pole.

18. The electronics system of claim 14, wherein the semiconductor switch is a transistor having a gate, a drain, and a source, the gate being coupled as the control terminal, the drain being coupled as the first pole, and the source being coupled as the second pole.

19. The electronics system of claim 12, wherein the power electronics system further includes:

a second single-phase transient voltage suppressor circuit coupled between the second transmission line and ground; and,

a third single-phase transient voltage suppressor circuit coupled between the third transmission line and ground.

20. The electronics system of claim 12, wherein the power electronics system further includes a three-phase transient voltage suppressor circuit coupled to the first, second, and third transmission lines, the three-phase transient voltage suppressor circuit comprising:

a three-phase rectifier circuit having a first input, a second input, a third input, a first output, and a second output, wherein the first input is coupled to the first transmission line, the second input is coupled to the second transmission line, and the third input is coupled to the third transmission line;

a second positive rail coupled to the first output of the three-phase rectifier circuit;

a second negative rail coupled to the second output of the three-phase rectifier circuit;

a second clamping circuit coupled between the second positive and negative rails, the second clamping circuit being operative to set the clamping voltage and to dissipate charge stored in the second capacitor when the second capacitor is charged to a voltage exceeding the clamping voltage such that the voltage

of the second capacitor is reduced to the clamping voltage.

21. The electronics system of claim 20, wherein the second clamping circuit comprises a resistor having a first terminal coupled to the second positive rail and a second terminal coupled to the second negative rail.

22. The electronics system of claim 20, wherein the second clamping circuit comprises:

a zener diode having a cathode and an anode, the cathode being coupled to the second positive rail, wherein a zener voltage of the zener diode sets a clamping voltage of the second positive rail;

a dissipating resistor having a first terminal and a second terminal, the first terminal of the dissipating resistor being coupled to the second positive rail; and

a semiconductor switch having a first pole coupled to the second terminal of the dissipating resistor, a second pole coupled to the positive rail, and a control terminal coupled to the anode of the zener diode, the semiconductor switch for coupling the second positive rail to the second negative rail when a voltage of the second positive rail exceeds the clamping voltage of the second positive rail.

23. The electronics system of claim 12, wherein the electrical machine is a variable speed motor.

24. The electronics system of claim 12, wherein the electrical machine is a variable speed generator.

25. A electronics system comprising:

an electrical machine;

a first transmission line coupled to the electrical machine for transmitting a first phase of an alternating current (AC) electrical signal;

a second transmission line coupled to the electrical machine for transmitting a second phase of the AC electrical signal;

a third transmission line coupled to the electrical machine for transmitting a third phase of the AC electrical signal; and

a transient voltage suppressor circuit coupled to the first transmission line, the second transmission line, the third transmission line, and ground, the transient voltage suppressor circuit including:

a rectifier circuit having a first input, a second input, a third input, fourth input, a first output, and a second output, wherein the first input is coupled to the first transmission line, the second input is coupled to the second transmission line, the third input is coupled to the third transmission line, and the fourth input is coupled to ground;

a positive rail coupled to the first output of the rectifier circuit;

a negative rail coupled to the second output of the rectifier circuit;

a capacitor coupled between the positive and negative rails; and

a clamping circuit coupled between the positive and negative rails, the clamping circuit being operative to set a clamping voltage and to dissipate charge stored in the capacitor when the capacitor is charged to a voltage exceeding the clamping voltage such that the voltage of the capacitor is reduced to the clamping voltage.

26. The electronics system of claim 25, wherein the clamping circuit comprises a resistor having a first terminal coupled to the positive rail and a second terminal coupled to the negative rail.

27. The electronics system of claim 25, wherein the clamping circuit comprises:

a zener diode having a cathode and an anode, the cathode being coupled to the positive rail, wherein a zener voltage of the zener diode sets a clamping voltage of the positive rail;

a dissipating resistor having a first terminal and a second terminal, the first terminal being coupled to the positive rail; and

a semiconductor switch having a first pole coupled to the second terminal of the dissipating resistor, a second pole coupled to the negative rail, and a control terminal coupled to the anode of the zener diode, the semiconductor switch for coupling the positive rail to the negative rail when a voltage of the positive rail exceeds the clamping voltage.

28. The electronics system of claim 27, wherein the first single-phase transient voltage suppressor circuit further includes at least one additional zener diode coupled between the zener diode and the control terminal of the semiconductor switch such that a sum of the zener voltage of the zener diode and zener voltages for each of the additional zener diodes sets the clamping voltage of the positive rail.

29. The electronics system of claim 28, wherein a current limiting resistor is coupled between the positive rail and the cathode of the zener diode.

30. The electronics system of claim 27, wherein the semiconductor switch is a transistor having a base, an emitter, and a collector, the base being coupled as the control terminal, the collector being coupled as the first pole, and the emitter being coupled as the second pole.

31. The electronics system of claim 27, wherein the semiconductor switch is a transistor having a gate, a drain, and a source, the gate being coupled as the control terminal, the drain being coupled as the first pole, and the source being coupled as the second pole.

32. The electronics system of claim 25, wherein the electrical machine is a variable speed motor.

33. The electronics system of claim 25, wherein the electrical machine is a variable speed generator.

34. A electronics system comprising:
an electrical machine;
a first transmission line coupled to the electrical machine for transmitting a first phase of an alternating current (AC) electrical signal;
a second transmission line coupled to the electrical machine for transmitting a second phase of the AC electrical signal;
a third transmission line coupled to the electrical machine for transmitting a third phase of the AC electrical signal; and
a transient voltage suppressor circuit coupled to the first transmission line, the second transmission line, and the third transmission line, the transient voltage suppressor circuit including:
a rectifier circuit having a first input, a second input, a third input, a first output, and a second output, wherein the first input is coupled to the first transmission line, the second input is coupled to the second transmission line, and the third input is coupled to the third transmission line;
a positive rail coupled to the first output of the rectifier circuit;
a negative rail coupled to the second output of the rectifier circuit;

a capacitor coupled between the positive and negative rails; and

a clamping circuit coupled between the positive and negative rails, the clamping circuit being operative to set a clamping voltage and to dissipate charge stored in the capacitor when the capacitor is charged to a voltage exceeding the clamping voltage such that the voltage of the capacitor is reduced to the clamping voltage.

35. The electronics system of claim 34, wherein the clamping circuit comprises a resistor having a first terminal coupled to the positive rail and a second terminal coupled to the negative rail.

36. The electronics system of claim 34, wherein the clamping circuit comprises:

a zener diode having a cathode and an anode, the cathode being coupled to the positive rail, wherein a zener voltage of the zener diode sets a clamping voltage of the positive rail;

a dissipating resistor having a first terminal and a second terminal, the first terminal being coupled to the positive rail; and

a semiconductor switch having a first pole coupled to the second terminal of the dissipating resistor, a second pole coupled to the negative rail, and a control terminal coupled to the anode of the zener diode, the semiconductor switch for coupling the positive rail to the negative rail when a voltage of the positive rail exceeds the clamping voltage.

37. The electronics system of claim 36, wherein the first single-phase transient voltage suppressor circuit further includes at least one additional zener diode coupled between the zener diode and the control terminal of the semiconductor switch such that a sum of the zener voltage of the zener diode and zener voltages for each of the additional zener diodes sets the clamping voltage of the positive rail.

38. The electronics system of claim 37, wherein a current limiting resistor is coupled between the positive rail and the cathode of the zener diode.

39. The electronics system of claim 34, wherein the semiconductor switch is a transistor having a base, an emitter, and a collector, the base being coupled as the control terminal, the collector being coupled as the first pole, and the emitter being coupled as the second pole.

40. The electronics system of claim 34, wherein the semiconductor switch is a transistor having a gate, a drain, and a source, the gate being coupled as the control terminal, the drain being coupled as the first pole, and the source being coupled as the second pole.

41. The electronics system of claim 34, wherein the electrical machine is a variable speed motor.

42. The electronics system of claim 34, wherein the electrical machine is a variable speed generator.

43. A circuit for suppressing transient voltages in an electrical signal transmitted by a first transmission line, the circuit comprising:

a full-wave rectifier circuit having a first input, a second input, a first output, and a second output, wherein the first input is coupled to the first transmission line and the second input is coupled to a second transmission line;

a positive rail coupled to the first output of the full-wave rectifier circuit;

a negative rail coupled to the second output of the full-wave rectifier circuit;

a capacitor coupled between the positive and negative rails;

a zener diode having a cathode and an anode, the cathode being coupled to the positive rail, wherein a zener voltage of the zener diode sets a clamping voltage of the positive rail;

a dissipating resistor having a first terminal and a second terminal, the first terminal being coupled to the positive rail; and

a semiconductor switch having a first pole coupled to the second terminal of the dissipating resistor, a second pole coupled to the negative rail, and a control terminal coupled to the anode of the zener diode, the semiconductor switch for coupling the positive rail to the negative rail when a voltage of the positive rail exceeds the clamping voltage.

44. The circuit of claim 43, wherein the circuit further includes at least one additional zener diode coupled between the zener diode and the control terminal of the semiconductor switch such that a sum of the zener voltage of the zener diode and zener voltages for each of the additional zener diodes sets the clamping voltage of the positive rail.

45. The circuit of claim 44, wherein a current limiting resistor is coupled between the positive rail and the cathode of the zener diode.

46. A circuit for suppressing transient voltages in an electrical signal transmitted by a first transmission line, the circuit comprising:

a full-wave rectifier circuit having a first input, a second input, a first output, and a second output, wherein the first input is coupled to the first transmission line and the second input is coupled to a second transmission line;

a positive rail coupled to the first output of the full-wave rectifier circuit;

a negative rail coupled to the second output of the full-wave rectifier circuit;

a capacitor coupled between the positive and negative rails;

a resistor having a first terminal and a second terminal, the first terminal being coupled to the positive rail and the second terminal being coupled to the negative rail, the resistor being operative to dissipate charge stored in the capacitor when a voltage of the capacitor is greater than a clamping

voltage such that the voltage of the capacitor is reduced to the clamping voltage.

47. A method for suppressing transient voltages that exceed a predfined clamping voltage in an electrical signal, comprising the steps of:

rectifying the electrical signal to output a rectified signal;

charging a capacitor having a first terminal and a second terminal to a first voltage using the rectified signal, wherein the first voltage is equal to at least the clamping voltage; and

discharging the capacitor to the clamping voltage if the first voltage exceeds the clamping voltage.

48. The method claim 47, wherein the method further comprises the steps of:

sensing by a zener diode that the first voltage exceeds the clamping voltage;

switching on a transistor in response to the zener diode sensing that the first voltage exceeds the clamping voltage, wherein the transistor couples the first terminal of the capacitor to the second terminal of the capacitor;

conducting current from the first terminal of the capacitor to the second terminal of the capacitor through a resistor such that power is dissipated in the resistor;

sensing by the zener diode that the capacitor is charged to the clamping voltage; and

switching off the transistor in response to the zener diode sensing that the the capacitor is charged to the clamping voltage such that current flow through the resistor stops.

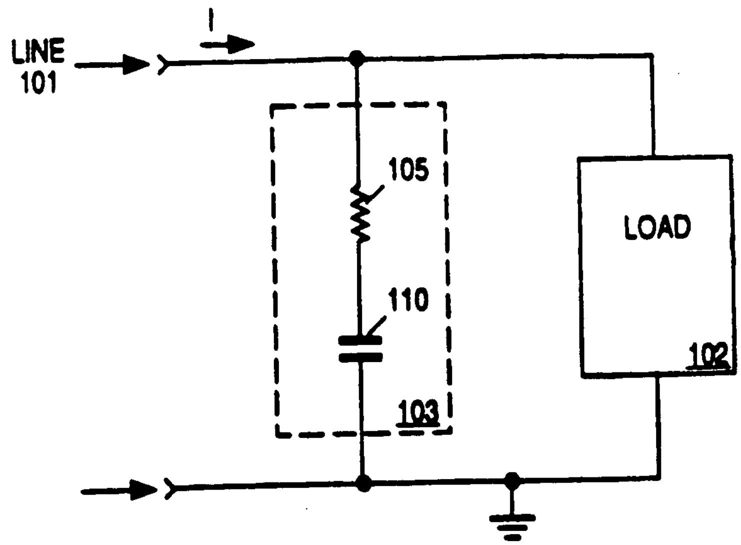


FIG. 1 (PRIOR ART)

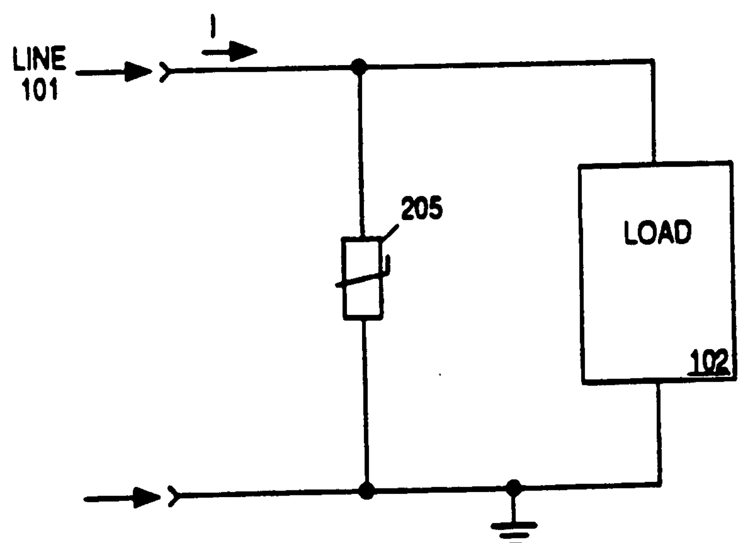


FIG. 2 (PRIOR ART)

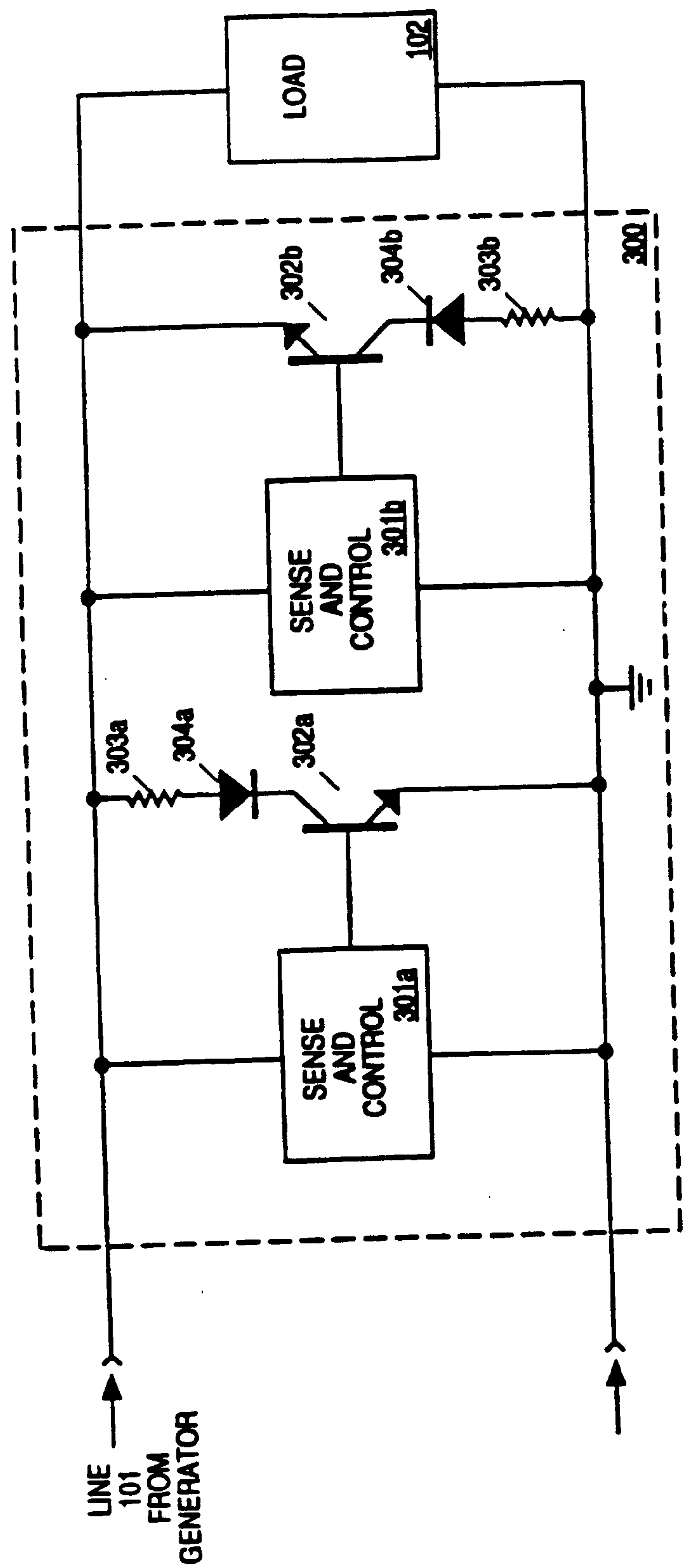
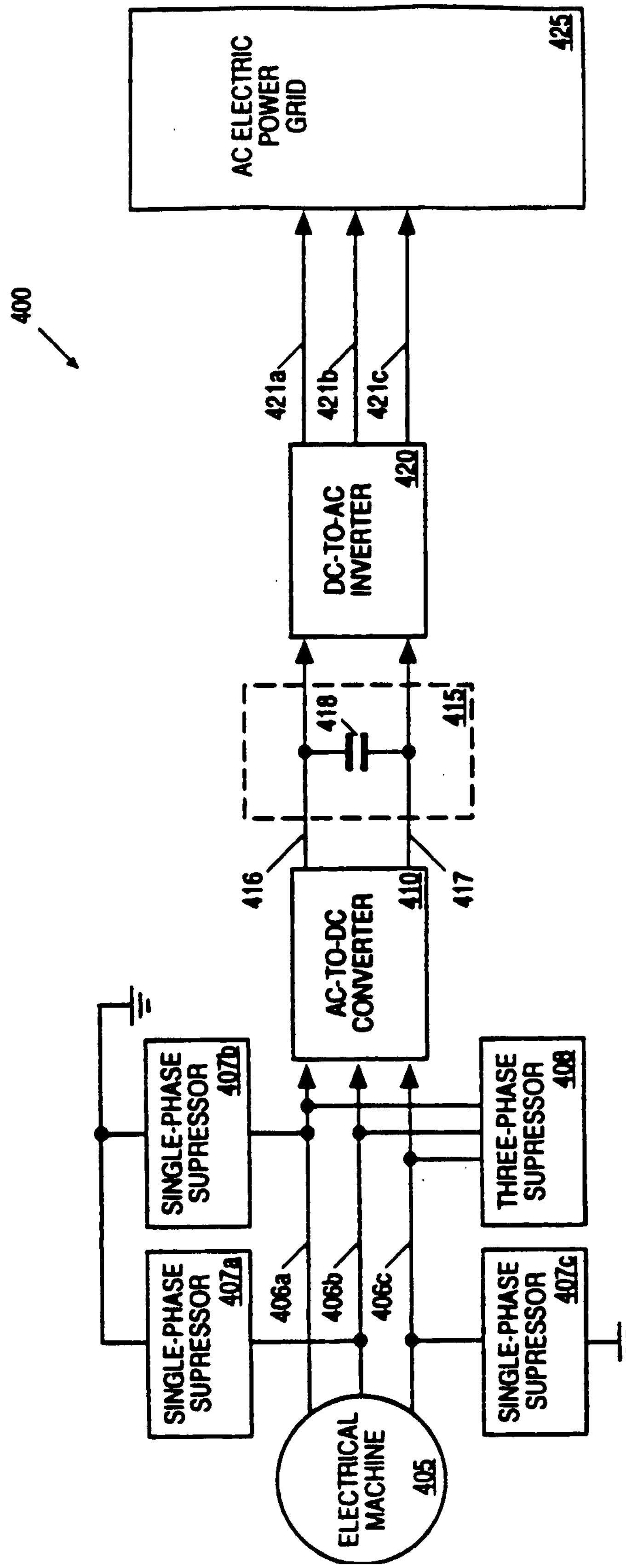
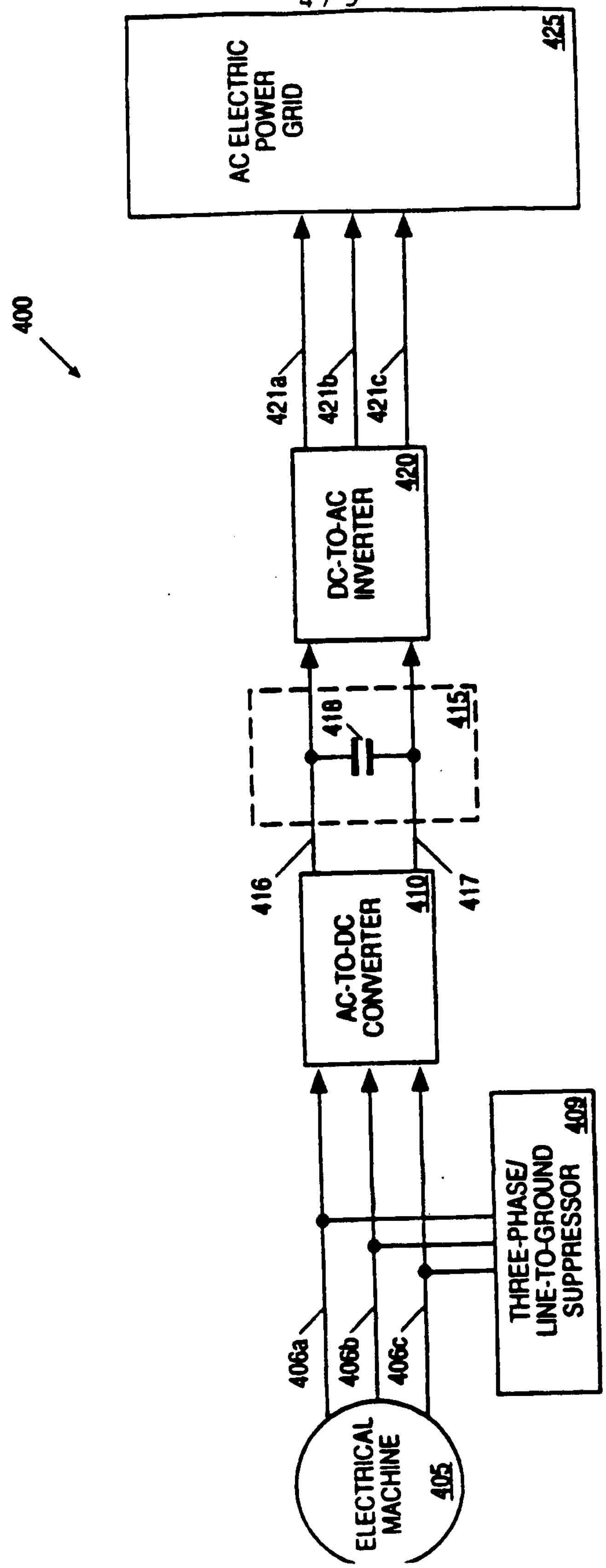


FIG. 3 (PRIOR ART)



AC ELECTRIC POWER GRID
425
400
421a
421b
421c
DC-TO-AC INVERTER
420
418
415
416
417
AC-TO-DC CONVERTER
410
SINGLE-PHASE SUPRESSOR
407b
THREE-PHASE SUPRESSOR
408
406a
406b
406c
SINGLE-PHASE SUPRESSOR
407a
SINGLE-PHASE SUPRESSOR
407c
ELECTRICAL MACHINE
405

FIG. 4a


AC ELECTRIC POWER GRID
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400
421a
421b
421c
DC-TO-AC INVERTER
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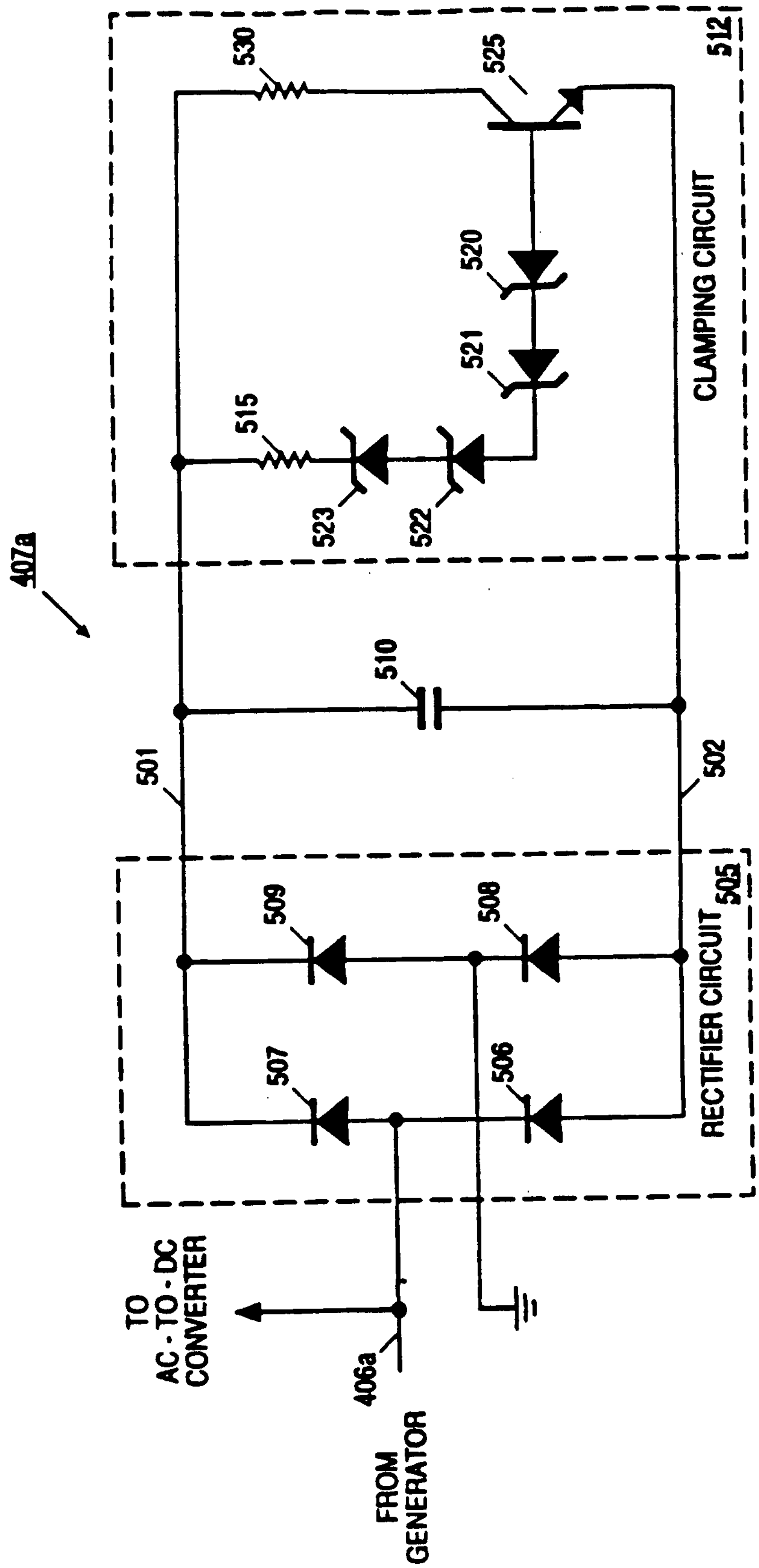
418
415
416
417
AC-TO-DC CONVERTER
410
THREE-PHASE/ LINE-TO-GROUND SUPPRESSOR
409
406a
406b
406c
ELECTRICAL MACHINE
405

FIG. 4b


407a
530
525
512
520
521
515
523
522
CLAMPING CIRCUIT
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501
502
509
508
507
506
RECTIFIER CIRCUIT
505
TO
AC-TO-DC
CONVERTER
406a
FROM
GENERATOR

FIG. 5

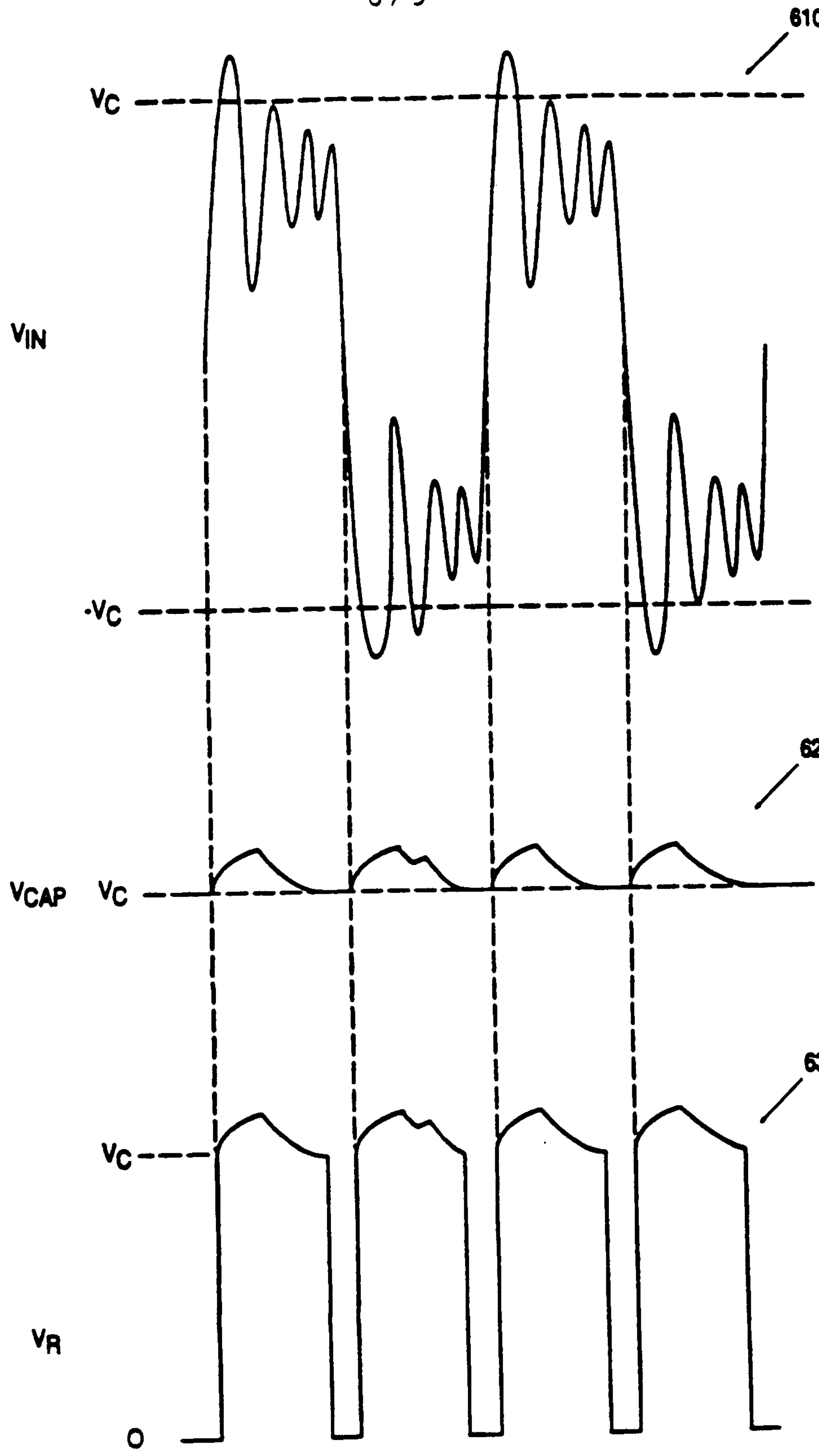


FIG. 6a

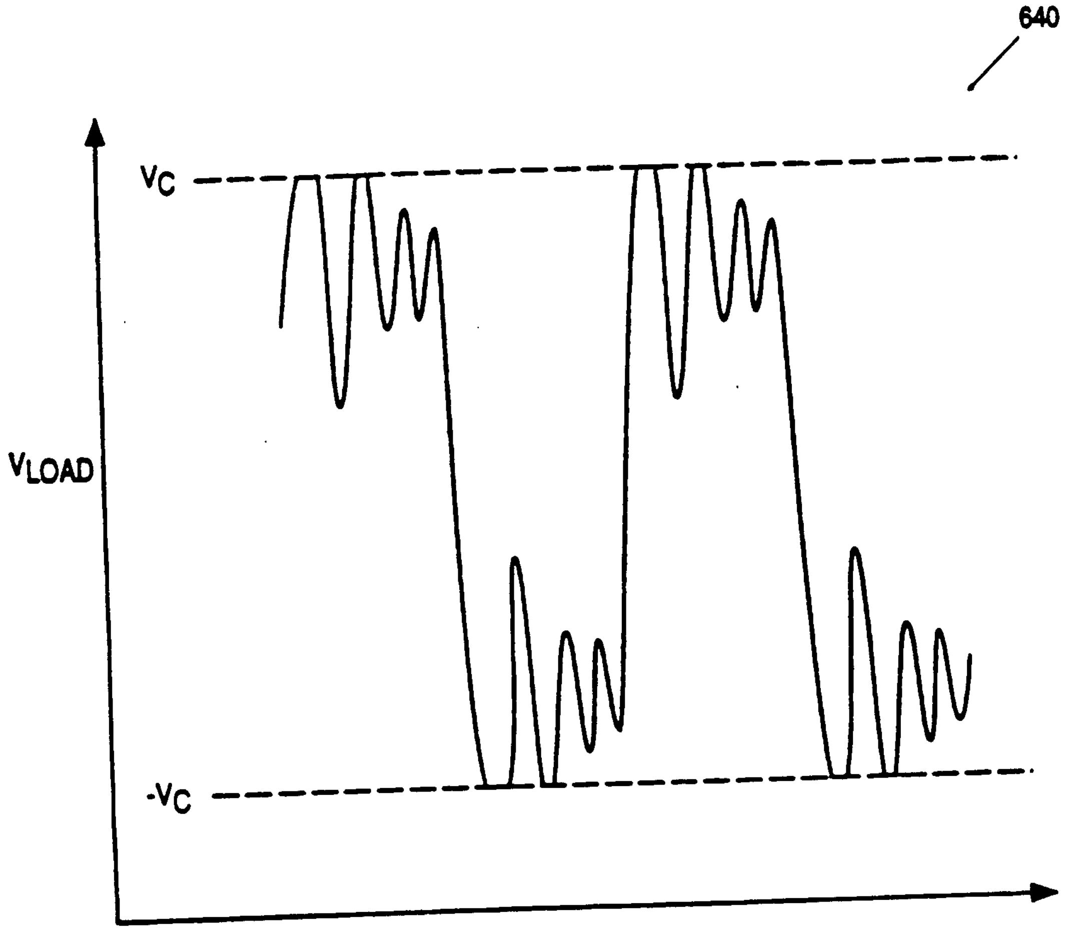
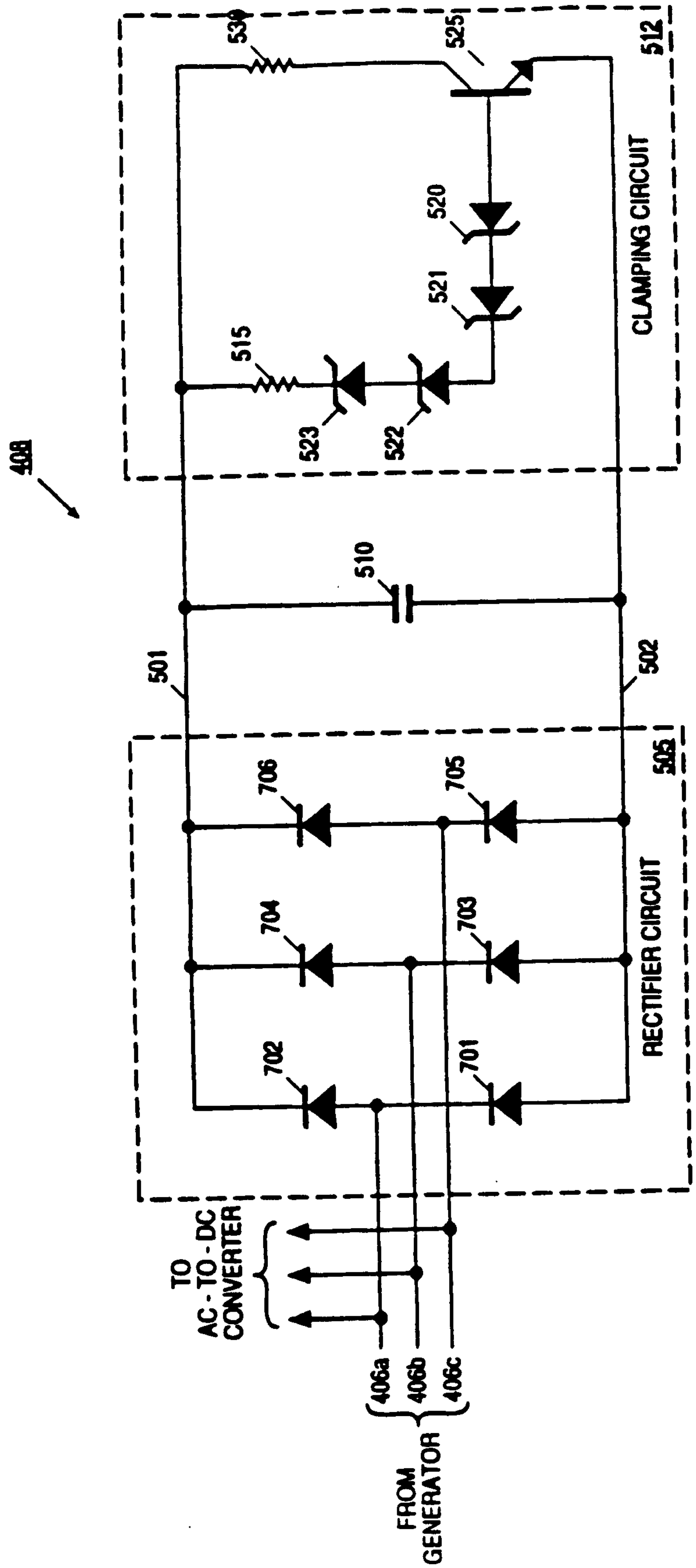


FIG. 6b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CLAMPING CIRCUIT
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515
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502
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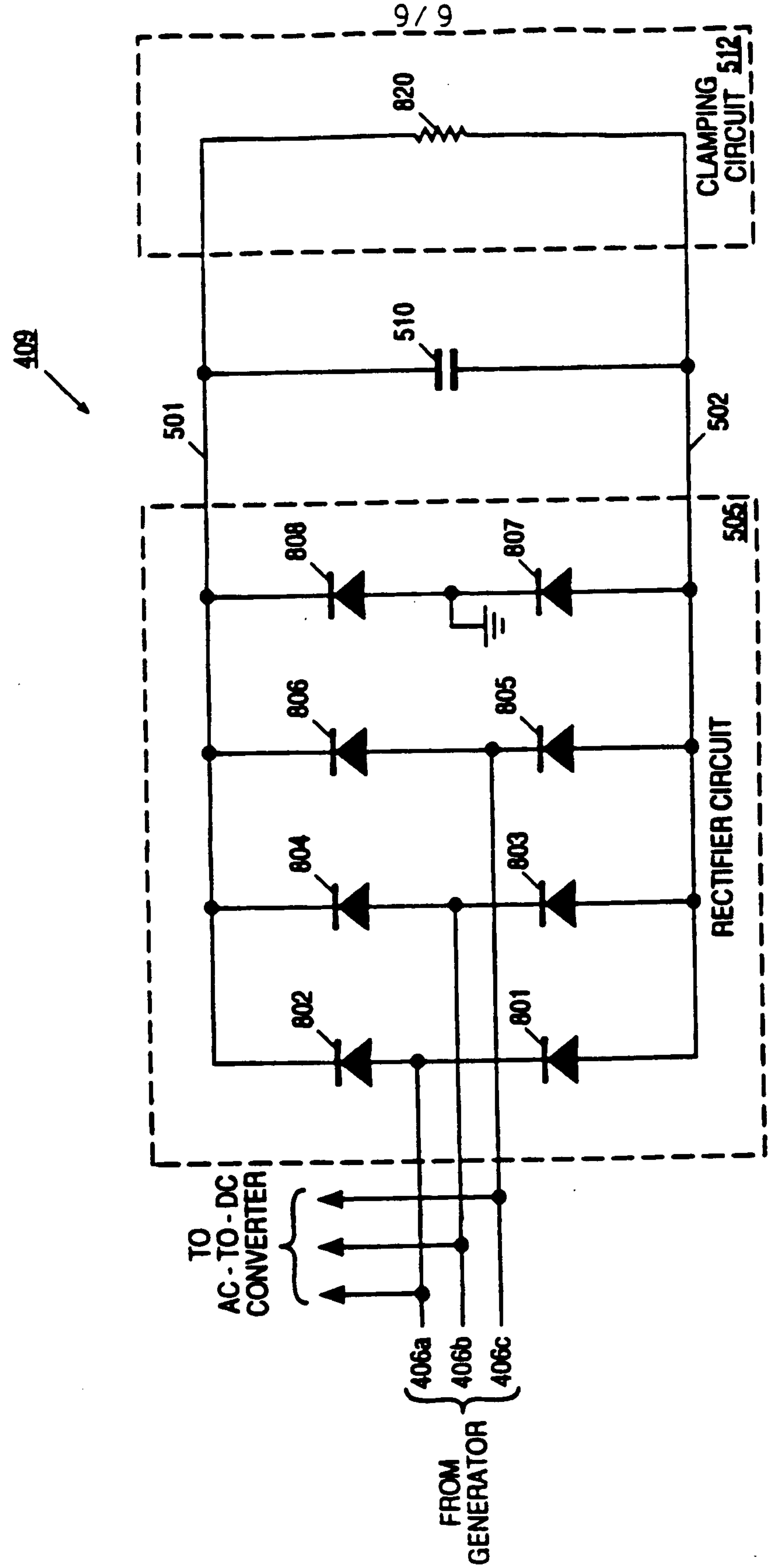
702
701
RECTIFIER CIRCUIT
TO AC-TO-DC CONVERTER
406a
406b
406c
FROM GENERATOR

FIG. 7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501
502
505
808
807
806
805
804
803
802
801
RECTIFIER CIRCUIT
TO AC-TO-DC CONVERTER
406a
406b
406c
FROM GENERATOR

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/13275

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :HO2H 9/04; HO2H 3/22
US CL :361/56, 91, 111
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 361/56, 91, 33, 21, 111

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 5,157,574 (TUUSA) 20 October 1992, see entire document.	1-48
Y	US, A, 4,870,528 (HARFORD) 26 September 1989, see entire document.	1-48
Y	US, A, 4,321,644 (BRASFIELD) 23 March 1982, see entire document.	1-48
Y	US, A, 4,271,446 (COMSTOCK) 02 June 1981, see entire document.	1-48

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
06 FEBRUARY 1996

Date of mailing of the international search report
28 FEB 1996

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